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Project Title: Upwelling-Induced Primary Productivity in Coastal Waters of the Black Sea: Impact on Algorithms for Remote Sensing

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This research program was a collaborative effort to investigate the impact of rapid changes in the water column during coastal upwelling on biological and optical properties. These properties are important for constructing region or event-specific algorithms for remote sensing of pigment concentration and primary productivity and for comparing these algorithms with those used for the development of large scale maps from ocean color. We successfully achieved the primary objective of this research project which was to study *in situ* the dynamics of rapid spatial and temporal changes in properties of the water column during coastal upwelling off the Crimean Coast in the Black Sea. The work was a collaborative effort between a group of biological and physical oceanographers from the Woods Hole Oceanographic Institution and from two oceanographic research institutions in the Crimea, Ukraine, located near the study site, the Marine Hydrophysical Institute (MHI) and the Institute of Biology of the Southern Seas (IBSS). The site was an ideal experimental model, both from a technical and economic standpoint, because of the predictable summer upwelling that occurs in the region and because of the availability of both a ship on call and laboratory and remote sensing facilities at the nearby marine institutes. We used a combination of shipboard measurements and remote sensing to investigate the physical evolution of rapid upwelling events and their impact on phytoplankton and water column optical properties. The field work involved a two day cruise for mooring deployment and a three day baseline survey cruise, followed by an eleven day primary cruise during a summer upwelling event (anticipated by monitoring local winds and tracked by remote sensing imagery). An MHI ship was outfitted and used for these purposes.

Physical Oceanography Component

The physical oceanographic portion of the investigation was very successful. The primary goal was to characterize the spatial and temporal variability of upwelled water between Cape Khersones and Cape Sarych along the Crimean Peninsula. In order to attain this goal, we deployed three moorings with twelve current meters and then conducted a hydrographic test cruise, followed by the primary hydrographic survey. Major sampling was performed with a Seabird 911+ CTD, with temperature and salinity data of normal western standards. 180 CTD stations were collected between the two hydrographic cruises in a roughly 50 km by 40 km region with station spacing generally 5 to 10 km. This was the first time that such high spatial and temporal scales have been resolved in the continental shelf region of the northern Black Sea, and this is particularly important because this shelf area had been closed to all scientists previously for security reasons due to the proximity to the Sevastopol Naval facilities. Concurrent with the shipboard observations, wind data from Cape Khersones and the oceanographic platform at Katsively were collected along with all available AVHRR data for sea surface temperature.

The hydrographic data shows remarkable temporal and spatial variability in both the upwelled water and the offshore basin water penetrating onto the shelf. During a synoptic

upwelling event which developed during the main hydrographic cruise, the upwelling water contained surface fronts with temperature contrasts as large as 8 °C over 2.5 km. The most remarkable feature of the upwelled water, however, was the development of a narrow filament 5-10 km wide which was oriented offshore, perpendicular to the coast. Thus the survey results show that the upwelled water is transported rapidly from the coastline into the Rim Current and central basin of the Black Sea, on time scales of 2 to 4 days. The upwelled water which remained along the coast was transported westward at 10-20 cm/s, showing that along-shelf transport of the upwelled water was also important.

A big surprise in the structure of the upwelling filaments was the correspondence between the surface structure and salinity and density gradients beneath the seasonal pycnocline. The density gradients beneath the filament were consistent with offshore geostrophic flows, and the density gradients were relatively constant from depths of 20 m to the bottom, at 100 m. This strongly suggests that the development of the filaments is related to the onshore displacement of the Rim Current front by frontal eddies or meanders, and points out the importance of offshore forcing on the fate of the upwelled water.

Bio-Optical Component

Concurrent with the hydrographic survey, we conducted intensive sampling to characterize biological and optical properties along the Crimean coast of the Black Sea during spring 1996. In addition, a small amount of sampling was carried out in the same region in early summer of 1997. The sampling periods were selected to coincide with coastal upwelling events, with the objective of evaluating the effects of nutrient injection on relationships between phytoplankton and optical properties of surface waters.

We observed an upwelling event in 1996 while sampling in the period from June 7 to 23. Physical perturbations in the region were evident in sea surface temperature data from AVHRR imagery and were confirmed during sampling at sea. In conjunction with detailed hydrographic measurements, we successfully carried out the first simultaneous characterization of phytoplankton and optical properties in this region. This work was accomplished through extensive collaboration with our Ukrainian colleagues from IBSS and MHI.

New observations for this region include the documentation of a persistent two layer structure in biological and optical properties. Chlorophyll fluorescence and particle absorption coefficients showed subsurface maxima at depths between 20 and 40 m, with particle absorption caused predominantly by phytoplankton pigments (~80% at 440 nm). Near surface waters had generally lower particle absorption coefficients and different spectral characteristics. Detrital particles made approximately the same contribution to absorption independent of depth and the most dramatic changes in particle absorption were found to be caused by vertical differences in phytoplankton community structure. Pigment biomass was highest in the mid-water column, below the pycnocline, with the upper layer dominated by nanophytoplankton and a shift toward microplankton in deeper waters. The most dramatic taxonomic change was a large decrease in the abundance of coccolithophores below about 20 m and absorption spectra typically exhibited an increasing importance of cyanobacteria, along with evidence for low-light acclimation, in deeper waters. This vertical structure in phytoplankton properties was associated with lower diffuse attenuation coefficients for irradiance and lower reflectance at blue-green wavelengths in near surface waters, compared to below the pycnocline.

Photosynthetic properties of the phytoplankton also showed pronounced vertical variability. Rates of photosynthesis were generally highest in the top 20 m and the phytoplankton exhibited characteristic physiological responses to light intensity. In surface waters, the quantum yield for carbon fixation was very low (~0.01 mol quanta (mol C)$^{-1}$) consistent with acclimation to high irradiance. At the subsurface phytoplankton maximum, quantum yields were higher (~0.03 mol quanta (mol C)$^{-1}$), but still low compared with the theoretical maximum of 0.1- 0.12 mol quanta (mol C)$^{-1}$. Bulk rates of photosynthesis were approximately 20 mg C m^{-3} d^{-1} in the upper water column.

Due to a combination of relatively fast time scales associated with advective processes and shallow source depth for upwelled waters, we did not observe a strong biological response to the upwelling in mid-June 1996; neither the biomass nor the physiological status of the phytoplankton changed dramatically during the sampling period. Further study of this region will be necessary to identify under what conditions this result can be expected to prevail.

To date, two manuscripts on this work have been submitted to journals. The first, "Upwelling and Eddy Development along the Crimean Coast: Observations and Numerical Model Results" by K. Brink, G. Gawarkiewicz, G. Korotaev, V. Koznyrev, E. Mikhaelova, and S. Stanichny, was recently submitted to Continental Shelf Research. The second, "Synoptic Upwelling and Cross-shelf Transport Processes along the Crimean Coast in the Black Sea" by G. Gawarkiewicz, G. Korotaev, S. Stanichny, L. Repetin, and D. Soloviev, was submitted two months ago to Continental Shelf Research and is presently under review. The latter work will be presented by G. Korotaev at the European Geophysical Society meeting in Nice, France, in April 1998. Additional results are currently being prepared for publication: "Phytoplankton, photosynthesis and optical properties in coastal waters of the northern Black Sea in spring 1996" by H.M. Sosik and T. Churilova.

In addition to the work performed during the summer of 1996, AVHRR data were collected in 1997, along with a brief cruise to determine the hydrographic, optical and biological properties over the shelf. Some future work on this may appear depending on the conditions in the Ukraine.